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CHEMICAL AND ISOTOPIC CHARACTERISTICS OF THERMAL FLUIDS IN THE LONG VALLEY CALDERA LATERAL FLOW SYSTEM, CALIFORNIA

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ABSTRACT

Chemical and isotopic data of thermal waters in Long Valley caldera have been used to identify both the origins and characteristics of the fluids and to evaluate mixing and boiling processes occurring within the lateral flow system of the caldera. Recharge to the Long Valley geothermal system occurs in the western part of the caldera with the water being heated at depth and flowing laterally eastward in the subsurface. The lateral flow system was recently intersected by the Shady Rest Continental Scientific Drilling Program (CSDP) corehole at 335 m (1100 ft) with fluids in this 202°C zone being more concentrated than non-boiled fluids to the east. As the Na-K-HCO_3-Cl thermal fluids flow eastward, they are increasingly mixed with isotopically depleted, dilute groundwaters similar to cold waters east of Lake Crowley. Near surface boiling of Casa Diablo well fluids at 100°C forms waters with the compositions of Colton and Casa Diablo hot springs. Waters to the east of the Casa Diablo area are mixtures of meteoric water and boiled thermal fluids with a composition close to that of Colton Hot Spring. There is no correlation between ^3H and ^{36}Cl in thermal fluids or between these components and conservative species, and it appears that cold fluids involved in mixing must be relatively old waters, low in both meteoric ^3H and ^{36}Cl.

INTRODUCTION

Long Valley is an elliptically-shaped caldera located at the boundary between the Sierra Nevada and Basin and Range tectonic provinces in east-central California. The caldera formed 0.7 Ma with the eruption of 600 km^3 of the Bishop Tuff. Between 0.6 and 0.1 Ma, rhyolites, rhyodacites and basalts were extruded around the resurgent dome which is located in the west-central portion of the caldera. The Inyo domes, located in the western third of the caldera, are recent rhyolitic eruptive domes with ages as young as 500 to 600 years and possibly were fed by the Inyo dike chain. Mammoth Mountain, which is at the southern terminus of the Inyo dike chain, ranges in age from 250,000 yr at its base to 50,000 yr at the summit. The geology and geologic history of the Long Valley caldera has been described by Bailey et al. (1976) and Bailey and Koeppen (1977).

Characteristics of the geothermal system associated with the caldera have been studied by several investigators (Mariner and Willey, 1976; Sorey et al., 1978; Blackwell, 1985; Farrar et al., 1985; Sorey, 1985; Sorey et al. 1986; and Shevenell et al., 1986). According to Sorey (1985), recharge to the hydrothermal system occurs on the western edge of the caldera along the Sierra Nevada front. Meteoric water then percolates downward and is heated at depth by a relatively young intrusion, which is probably associated with the Inyo dike chain. Thermal fluids flow laterally toward the east, around the southern edge of the resurgent dome, and become increasingly mixed with dilute meteoric groundwaters to form the more diluted fluids found within the caldera.

Several shallow holes have been drilled in the Long Valley caldera that show evidence of intersecting the lateral flow system, with temperature reversals occurring in the upper portions of the drill holes (Sorey et al., 1978; Blackwell, 1985). A recent CSDP hole was cored near the Shady Rest campground in Mammoth Lakes in the western part of the caldera. The Shady Rest corehole exhibits strong evidence of intersecting the lateral flow system in the western caldera region (Table 1). The samples listed in Table 1 were collected and analyzed in 1984, 1985, and 1986 according to the procedures of Trujillo et al., 1987. This report combines chemical and isotopic data from the springs within the caldera, from fluids in the Casa Diablo wells, and from fluids in the Shady Rest corehole to evaluate mixing and boiling processes in the Long Valley lateral flow system. This characterization of the thermal fluids associated with Long Valley is part of a background study for future CSDP projects and is designed to help identify future drilling targets.

SHADY REST COREHOLE

In June 1986, the Shady Rest hole was continuously cored in the southwestern moat area of Long Valley caldera to a completed depth of 426 m (1397 ft) and a maximum temperature of

Table 1. Chemical[a] and Isotopic[b] Data of Thermal and Nonthermal Waters[c] in Long Valley Caldera.

Sample No.	Name	Date Collected	Temp. (°C)	Field pH	SiO_2	Na	K	Li	Ca	Mg
LV86-9	Shady Rest Core Hole at 1100 ft	11/86	202	5.94	290	374	42	2.78	9.9	0.17
LV86-11	Shady Rest Core Hole at 1100 ft	11/86	202	5.94	290	382	45	2.83	7.3	0.12
LV85-12[d]	Casa Diablo Well #1	5/85	168	8.75	275	418	40.0	3.40	1.8	0.15
LV85-23[d]	Casa Diablo Well #1	5/85	168	5.60	210	392	36.0	3.20	1.6	0.14
LV85-24[d]	Casa Diablo Well #3	5/85	171	6.10	245	378	38.0	3.00	2.0	0.18
LV86-13	Casa Diablo Well #3	11/86	170	6.07	255	336	32	2.66	5.5	0.20
MLV-8	Casa Diablo Hot Spring	11/84	95.4	8.50	280	420	34	3.27	1.6	0.12
MLV-25	Casa Diable Hot Spring	2/85	95.4	8.50	307	436	34	3.54	1.7	0.02
LV86-12	Casa Diablo Hot Spring	11/86	94.0	8.5	290	450	43	3.41	1.7	<0.01
MLV-11	Colton Hot Spring	11/84	95.0	8.75	249	395	24	3.05	2.9	0.02
MLV-26	Colton Hot Spring	2/85	93.5	8.35	280	395	23	3.13	2.0	0.01
MLV-12	Casa Diablo Pool	11/84	69.0	7.35	212	370	20	2.85	9.9	0.22
MLV-7	Hot Creek Hot Spring	11/84	85.9	8.19	138	375	20	2.55	5.3	0.27
MLV-27	Hot Creek Hot Spring	2/85	84.8	8.02	160	386	20	2.64	6.8	0.33
LV86-2	Hot Creek Hot Spring	5/86	94.0	8.4	135	379	19	2.54	9.5	0.5
LV86-6	Hot Creek Hot Spring	11/86	93.0	8.04	150	380	23	2.43	5.2	0.16
MLV-13	Little Hot Creek Hot Spring	11/84	82.7	7.15	86	400	22	2.76	23.9	0.63
LV86-7	Little Hot Creek Hot Spring	11/86	85.0	7.0	90	390	26	2.66	22.8	0.52
HC-1	Hot Creek Gorge Well	11/84	93.2	7.20	201	357	18.7	2.64	16.1	0.45
MLV-20	Meadow Hot Spring	11/84	67.2	6.81	200	234	36	1.70	4.1	0.66
MLV-17	Hot Spring North of Whitmore	11/84	57.1	7.92	119	303	23	2.2	14.8	0.39
MLV-18	Big Alkali Hot Spring	11/84	58.2	7.17	190	376	29	1.70	24.9	0.63
MLV-16	Whitmore Warm Spring	11/84	33.4	7.71	69	112	7.6	0.78	19.9	1.69
MLV-21	East Crowley Warm Spring	11/84	30.2	8.57	71	83	5.3	0.29	5.4	0.11
MLV-19	Big Spring	11/84	10.2	7.40	51	20	3.5	0.03	4.9	5.02
MLV-15	Fish Hatchery Spring	11/84	14.5	7.18	53	21	4.4	0.11	12.3	8.63
LV85-7[d]	Laurel Spring	5/85	11.8	8.55	21	6.1	1.2	<0.01	15.7	0.59
MLV-5	Red's Meadow Hot Spring	11/84	13.3	7.02	148	132	5.8	0.97	60.7	2.20
MLV-4	Soda Flat Spring	11/84	13.3	6.49	78	485	19	2.06	43.1	26.2

[a] Chemical analyses were performed by P. E. Trujillo, Jr. and Dale Counce, Los Alamos National Laboratory.

[b] Stable isotope analyses were performed by C. Janik, U.S.G.S., Menlo Park, CA; tritium analyses were performed by Dr. H. Gote Ostlund at the University of Miami while Cl data were provided by Dr. F. Phillips, New Mexico Institute of Mining and Technology, Socorro, NM.

[c] Springs are listed according to their locations from west to east within the caldera.

[d] Collected by C. Janik, USGS, Menlo Park, CA.

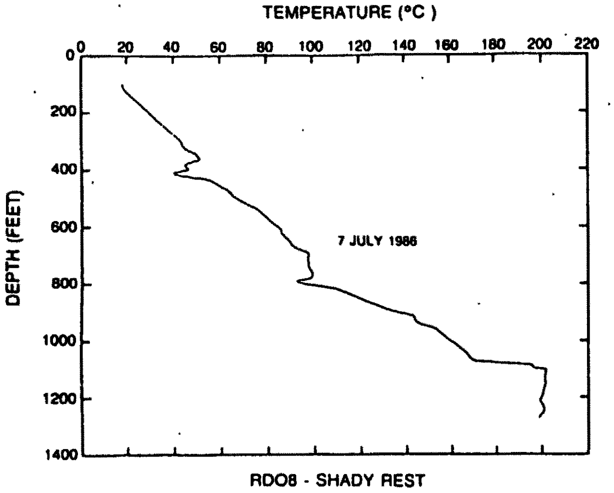

Fig. 1. Temperature profile of the CSDP Shady Rest corehole measured on July 7, 1987. The temperature log was run by Ron Jacobson and Bob Myers of Sandia National Laboratories.

202°C (Wollenberg, 1986). In July 1986 a temperature log of the hole was obtained, with the two lost circulation zones at 400 and 800 ft being quite evident (Fig. 1). Near 1000 ft, the temperature rises rapidly to 202°C and then becomes isothermal below 1100 ft. Because this rapid increase in thermal gradient suggests a thermal fluid inflow zone, the 1100 ft zone was perforated in late October 1986 by scientists from Lawrence Berkeley Laboratory, the U.S.G.S, and Sandia National Laboratories.

In November 1986 three wellbore volumes were bailed from the Shady Rest corehole. Following this, an in-situ fluid sample was obtained from the perforated, 202°C zone at 1100 ft using a gas-tight fluid sampler operated by Los Alamos National Laboratory scientists. The chemistry of the 1100 ft fluid zone verifies that the corehole intersected the lateral flow system. Sample LV86-9 (Table 1) was obtained with the in-situ sampler while LV86-11 was obtained with the bailer. Both samples chemically resemble thermal fluids identified east of the corehole.

Table 1 (cont)

Sample No.	Cl	F	HCO_3	SO_4	B	Br	NH_4	$\frac{^{36}Cl}{Cl} \times 10^{15}$	δD (‰)	$\delta^{18}O$ (‰)	^3H (TU)
LV86-9	279	8.65	610	141	12.2	--	2.6	--	-115.1	-14.29	--
LV86-11$_d$	296	10.2	466	138	12.3	0.5	0.04	--	-115.4	-14.30	1.40
LV85-12$_d$	270	10.10	374	124	11.80	0.6	0.21	17 ± 4	--	-14.34	--
LV85-23$_d$	244	10.10	425	119	11.10	0.5	0.31	--	-118.4	-14.72	--
LV85-24	238	9.50	423	116	11.40	0.5	0.29	--	--	-14.69	0.26
LV86-13	230	9.4	451	107	9.9	0.7	0.77	--	-117.7	-14.78	0.22
MLV-8	304	12.0	398	147	13.7	0.77	0.09	35 ± 3	-113.3	-13.27	0.35
MLV-25	290	12.2	283	136	13.7	0.70	0.09	--	--	--	--
LV86-12	317	13.7	268	144	13.3	0.5	0.02	--	-113.1	-13.66	0.33
MLV-11	269	9.9	345	131	11.6	<0.5	0.12	--	-117.1	-14.29	0.40
MLV-26	257	10.6	353	127	11.8	0.56	0.15	--	--	--	--
MLV-12	241	10.5	407	118	11.6	0.60	0.09	18 ± 4	-114.3	-13.05	0.62
MLV-7	214	9.0	564	89	10.0	0.50	0.06	10 ± 2	--	-14.93	0.23
MLV-27	208	8.8	558	90.7	10.2	0.57	0.12	--	--	--	--
LV86-2	205	9.15	572	88.2	11.5	0.3	0.24	--	--	--	--
LV86-6	223	9.92	409	95	10.7	0.3	0.45	--	-119.1	14.84	0.30
MLV-13	204	7.6	712	97	9.1	0.40	0.11	18 ± 5	--	-15.6	0.16
LV86-7	207	8.42	728	99	8.97	0.3	0.02	--	-122.7	-15.55	0.17
HC-1	195	7.7	565	86.0	7.7	0.53	0.33	--	--	--	--
MLV-20	201	7.8	133	114	9.1	2.7	<0.02	--	--	--	3.03
MLV-17	173	7.1	506	74	8.2	0.80	<0.02	47 ± 10	--	--	0.50
MLV-18	144	4.62	769	64	6.6	0.36	0.07	14 ± 3	-123.9	-16.09	0
MLV-16	54	2.48	230	33.1	2.74	0.15	<0.02	--	--	--	4.0
MLV-21	20	1.86	161	18	0.56	0.04	<0.02	--	--	--	0.28
MLV-19	4.5	0.45	76.3	4.7	0.20	<0.03	<0.02	--	-115.4	-15.83	--
MLV-15$_d$	3.7	0.28	113	9.3	0.07	<0.03	<0.02	--	--	-15.70	22.3
LV85-7	2.0	0.12	46.4	18.4	0.04	<0.1	<0.02	--	-126.5	16.97	8.23
MLV-5	6.6	4.64	495	32	1.75	<0.03	<0.02	--	--	14.98	2.32
MLV-4	290	2.86	1050	34	7.0	0.51	<0.02	23 ± 4	-108.2	-14.91	5.33

However, the corehole samples are slightly contaminated with drilling fluids as the samples contain high concentrations of Ca and ^3H which are also high in young local meteoric water used in the drilling muds. The Shady Rest borehole was not allowed to flow, and hence, the borehole was not completely flushed of the drilling fluid contaminants. Nevertheless, the Shady Rest samples, which occur 4 km west of Casa Diablo, up-gradient on the lateral flow system, are the most concentrated, non-boiled thermal fluids encountered in the flow system to date.

STABLE ISOTOPES

From stable isotope data, Sorey (1985) showed that recharge to the Long Valley thermal system occurs in the western part of the caldera along the Sierra Nevada front. All thermal waters in Long Valley fall to the right of the world meteoric water line on a plot of δD vs $\delta^{18}O$ (Fig. 2). The oxygen-18 enrichment of the thermal fluids suggests high temperature isotopic exchange between water and rock at

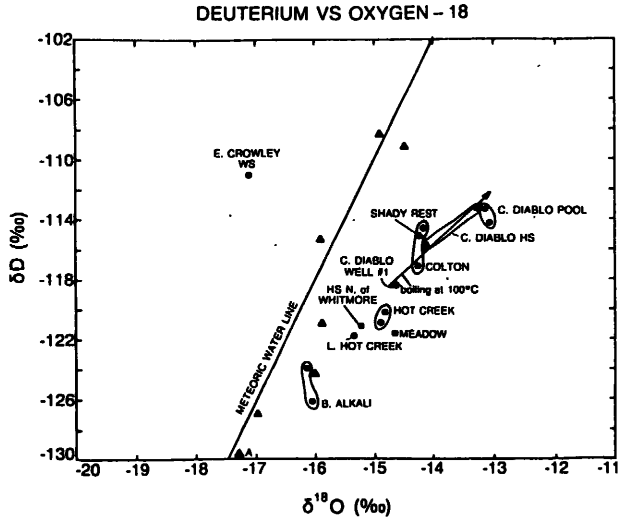

Fig. 2. Deuterium versus oxygen-18 for thermal and nonthermal waters in Long Valley caldera. Triangles represent cold, meteoric waters whereas dots represent thermal fluids. The triangle labeled A is the spring east of Lake Crowley of Mariner and Willey, 1976. Isotopic data used for this plot is located in Table 1.

depth. Figure 2 illustrates a trend between depleted isotopic compositions of springs in the Casa Diablo area toward the east at spring A, located east of Lake Crowley (Mariner and Willey,1976). Thermal fluids become increasingly depleted in deuterium and oxygen-18 from west to east along the lateral flow system (Table 1). Apparently, thermal waters become increasingly diluted towards the east with isotopically depleted meteoric water similar to spring A. Therefore, it appears that the diluting fluids that mix with thermal waters from the western part of the caldera originate from the eastern part of the caldera.

The stable isotope data of Fig. 2 and Table 1 also indicate that boiling occurs in the Casa Diablo area. If we assume that fluid in Casa Diablo well #1 is most representative of deep geothermal water beneath the site, then we can calculate that the isotopic enrichment in the Colton and Casa Diablo hot springs results from the boiling of Casa Diablo well fluids at 100°C. Therefore, Casa Diablo well fluids must rise, cool conductively to near 100°C, and boil in the near-surface to form slightly more concentrated fluids with the compositions of Colton and Casa Diablo hot springs. Additional evidence of boiling in the Casa Diablo area is presented in the following sections.

CHEMISTRY

The thermal fluids in Long Valley caldera are Na-K-HCO_3-Cl waters with total dissolved solids up to 1600 mg/ℓ in the western part of the caldera. Thermal fluids contain significant concentrations of As, B, F, Li and NH_4. Cation geothermometers, calculated from the fluid chemistry from the Casa Diablo wells, indicate equilibration temperatures between 210 and 220°C (Table 2). Silica geothermometers from the same fluids yield temperatures less than 200°C, possibly due to boiling and precipitation of SiO_2 at Casa Diablo. Cation geothermometer temperatures from the Shady Rest fluids indicate equilibration between 200 and 210°C, while the quartz conductively cooled geothermometer yields a temperature of 203°C, which is precisely the current temperature of the zone sampled at 335 m in this corehole.

Mixing is an important process occurring in the thermal fluids of the caldera. A consistent decrease in conservative species (Cl, B, Li, F) occurs from west to east as thermal fluids are increasingly mixed with dilute groundwaters originating from the east. A plot of B vs Cl (Fig. 3) illustrates a distinct mixing trend with thermal fluids becoming increasingly diluted along the lateral flow path toward the east. Boiling and mixing trends are coincident on the plot of Fig. 3 with the Shady Rest sample representing the most concentrated, unboiled thermal fluid encountered within the caldera. Thus fluids from the Shady Rest borehole are the most representative of end-member geothermal fluid. The Casa Diablo wells must, therefore, be slightly diluted versions of the Shady Rest fluids. The plot of Fig. 3 and the stable isotope data suggests that Casa Diablo hot

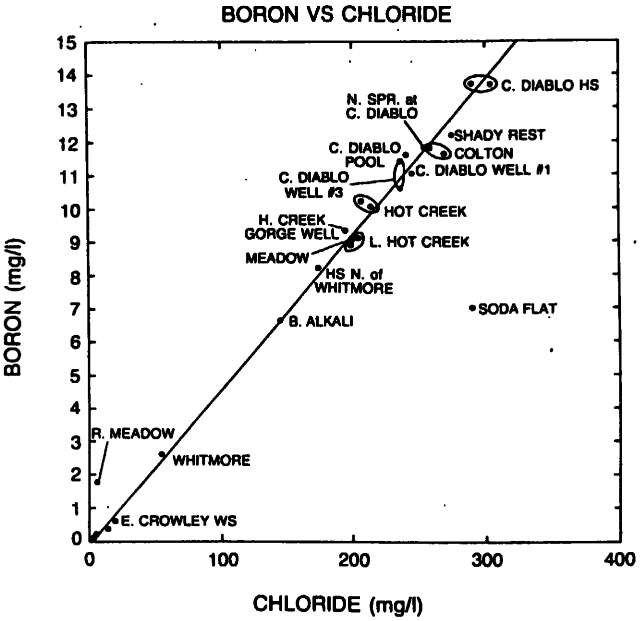

Fig. 3. Plot of B versus Cl of thermal and nonthermal waters in Long Valley caldera. The B and Cl data are tabulated in Table 1. The three low concentration points represent the compositions of samples MLV-19, MLV-15 and LV85-7 (Table 1).

Table 2. Chemical Geothermometer Temperatures (°C) of Selected Thermal Waters in Long Valley Caldera.

Sample	Name	Measured Temp(°C)	Qtz[a]	Qtz[b]	Chalcedony	Na-K	Na-K-Ca $\beta = 4/3$	Na-K-Ca $\beta = 1/3$	Mg Corr.
LV86-9	Shady Rest Core Hole at 1100 ft	202	191	203	190	207	211	209	209
LV85-12	Casa Diablo Well #1	168	188	199	185	213	293	219	219
LV86-13	Casa Diablo Well #3	170	183	194	178	213	217	203	203
LV86-12	Casa Diablo Hot Spring	94.0	191	203	190	213	304	221	221
MLV-26	Colton Hot Spring	93.5	189	200	187	175	243	187	187
LV86-6	Hot Creek Hot Spring	93.0	154	159	136	177	201	180	180
LV86-7	Little Hot Creek Hot Spring	85.0	129	129	103	185	155	173	173

[a] Adiabatically cooled.
[b] Conductively cooled.

spring, and possibly Colton hot spring, have been concentrated by boiling. The Soda Flat and Reds Meadow springs, located west of Mammoth Mountain, do not lie on the mixing trend identified by the thermal fluids within the caldera and must have distinct hydrologic and geochemical controls.

Both the stable isotope plot (Fig. 2) and the B vs Cl data (Fig. 3) suggest that mixing and boiling occur within the caldera, yet boiling cannot be uniquely distinguished from mixing. In order to isolate the two processes and determine if boiling of Casa Diablo well fluids forms fluids with the compositions of Colton and Casa Diablo hot springs, NH_4 data is examined. This species will partition itself between the liquid and vapor phases. The NH_4 versus Cl plot (Fig. 4) more clearly identifies the end-member, boiled, and mixed components of the thermal fluid. In order to verify that the trend on the right of Fig. 4 results from boiling, we first assume that Casa Diablo well fluids are slightly diluted Shady Rest fluids, and conductively cool to 100°C before boiling. Using Cl mass balance, we find that 9 and 19% steam loss from boiling of well fluids would form the springs at Colton and Casa Diablo. With these steam fractions and the gas distribution coefficient for NH_3 for single-stage boiling at 100°C (Henley et al., 1984), boiling of Casa Diablo well fluids with a steam loss of 9% would result in an NH_4 concentration of 0.14 mg/ℓ. This is the measured NH_4 concentration of Colton hot spring. Boiling with a 19% steam loss results in an NH_4 concentration of 0.09, again the measured NH_4 value of Casa Diablo hot spring. Therefore, the NH_4 and Cl data, combined with the evaluations made with the stable isotope and B data, indicate that boiling of Casa Diablo well fluids at 100°C with steam losses of 9 and 19% forms the fluids at Colton and Casa Diablo hot springs, respectively.

NH_4 and Cl concentrations were also calculated for boiled fluids with 1 to 25% steam loss. These values are represented by the curve on the right of the plot of Fig. 4. The NH_4 and Cl data also suggest a mixing trend. Mixing apparently occurs between boiled fluid similar to Colton hot spring and cool, dilute ground waters, with dilution increasing toward the east. Therefore, mixing within the caldera does not occur between end-member thermal water (i.e., Shady Rest) and dilute groundwater, but between boiled Casa Diablo well fluid, such as Colton hot spring, and dilute fluids from the east.

^3H AND ^{36}Cl

The ^3H and ^{36}Cl analyses were done for several of the thermal and nonthermal waters within the caldera to identify the relative ages of fluids and their depths of circulation (Table 1). All thermal fluids within the caldera are low in both ^3H and ^{36}Cl, however, there is no trend of increasing ^3H concentration with increasing ^{36}Cl. Also, there is no correlation between ^3H and ^{36}Cl and conservative species. If thermal waters were being diluted with young shallow groundwaters, one would expect an increase of

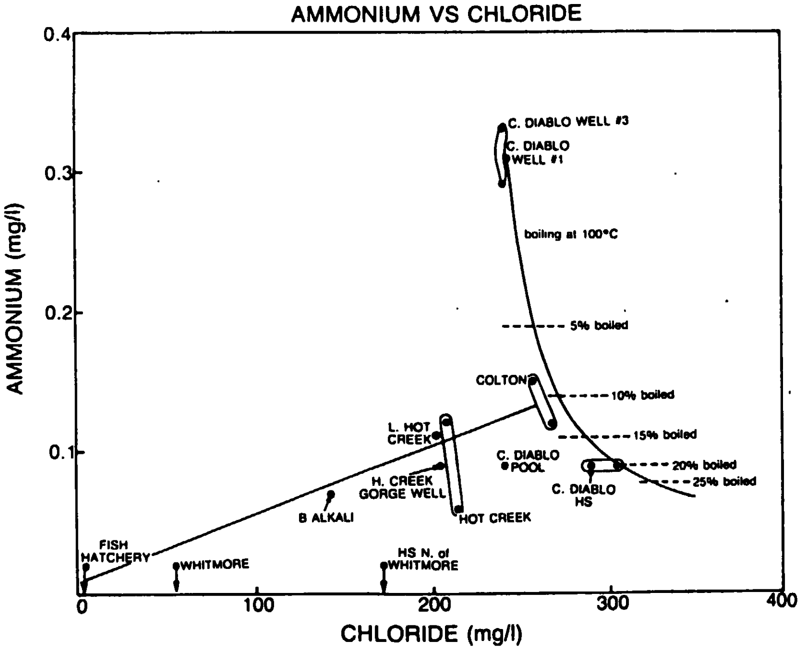

Fig. 4. NH_4 versus Cl for thermal and nonthermal waters in Long Valley caldera.

^{3}H and ^{36}Cl with decreasing total Cl content. Because this trend does not exist, mixing of thermal fluids does not occur with young near surface groundwaters. Except for the hot spring north of Whitmore and Meadow hot spring, it appears that most cold end-member fluids involved in mixing in the caldera must be relatively old, deeply circulating fluids, low in both meteoric ^{3}H and ^{36}Cl (Table 1). The relatively old age of the dilute waters implies that these waters must circulate fairly deeply before mixing with thermal waters in the caldera.

SYSTEM MODEL

The data discussed in the previous sections allow the presentation of a simplified model of the geothermal system in Long Valley. Figure 5 is a simplified cross-section which has been modified from the model proposed by Sorey (1985). Recharge to the thermal system occurs in the western part of the caldera with meteoric water percolating downward to some depth and being heated by a relatively recent intrusion at some point west of Shady Rest. From the results of the CSDP drilling in the vicinity of the Inyo dike chain (Eichelberger et al., 1985, 1986) and from the young ages of the Mammoth Mountain-Inyo dike chain area, the proposed intrusion must be dacitic to rhyoitic magma in the upper 3 km of the crust. Because low pressure fumaroles occur on Mammoth Mountain and Red's Meadow hot spring is representative of a steam heated spring, it is possible that major convective upflow occurs beneath Mammoth Mountain. Thermal fluids must rise along fault and fracture systems utilized by the young intrusives before flowing laterally toward the 335 m zone intersected by the Shady Rest corehole. As the fluid flows laterally to the east, it mixes slightly and conductively cools from 202°C measured at Shady Rest to 170°C at the Casa Diablo wells. In the Casa Diablo area, thermal waters must locally flow upward, cool conductively to near 100°C and boil at 100°C in a near-surface environment. The boiled fluids form waters with the compositions of Colton and Casa Diablo hot springs which are 9 and 19% boiled. Boiled fluid similar in chemical composition to Colton hot spring flows laterally and becomes increasingly diluted toward the east with the concentrations of conservative species decreasing toward the east. The stable isotope data indicate that the diluting fluids originate from the eastern and southern portions of the caldera. The ^{3}H and ^{36}Cl data show that the dilute water is relatively old and probably circulates deeply before rising to mix with the thermal waters within the caldera.

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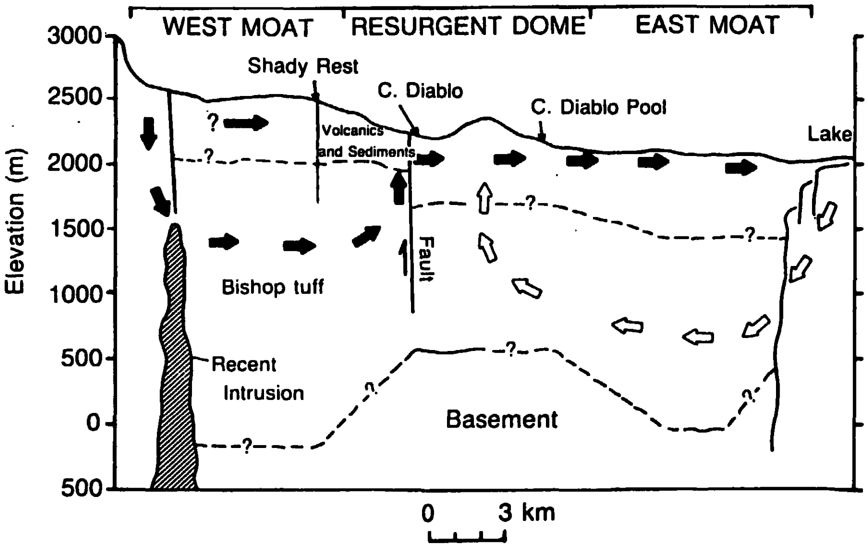

Fig. 5. Cross-section of Long Valley caldera from west to east illustrating proposed fluid flow paths. Lake refers to Lake Crowley.

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